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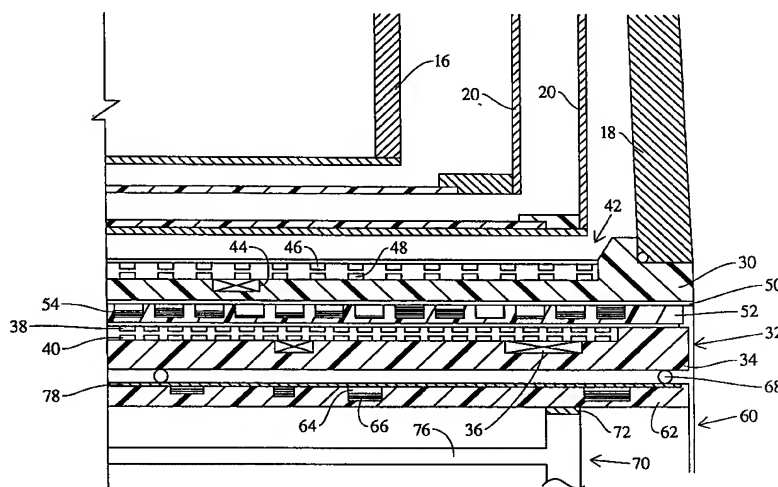
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(57) A toroidal housing (18), such as a vacuum dewar, contains magnets (10, 12) for generating a temporally constant magnetic field through a central bore (14). Gradient coils (32, 42) are mounted around the bore defining a space therebetween. A radio frequency shield (78) is disposed radially inward from the gradient coils. Inside the radio frequency shield, an inner shimming assembly (60) includes a dielectric cylinder (62) having annular grooves around its periphery. Segmented ferrous material (66) is arranged in annular

rings in the grooves. The ferrous material is segmented into small pieces electrically insulated from each other to limit radio frequency and gradient frequency eddy currents. A radio frequency coil (70) is mounted inside of the annular ferrous shims (66). Preferably, additional shim trays (52) which carry shims (54) are mounted in the space between the primary and secondary gradient coils.

**Fig. 2****EP 0 737 867 A1**

## Description

The present invention relates to a magnetic resonance apparatus and a method of shimming a magnetic resonance imaging apparatus. It finds particular application in conjunction with medical diagnostic magnetic resonance imaging and will be described with particular reference thereto. However, it is to be appreciated that the present invention also finds application in magnetic resonance spectroscopy and magnetic resonance imaging for other applications.

Heretofore, magnetic resonance imagers included a series of annular magnets which generated a temporally constant, generally uniform magnetic field through their common bores. In superconducting magnet designs, the magnets were encased in a vacuum dewar. Whether in a vacuum dewar or other housing, a patient receiving bore was defined through the magnets. In general, the longer the bore, the more uniform the magnetic field. Typically, the bore length was on the order of 1.5 to 2.0 meters. The uniformity of the magnetic field is generally characterized in terms of the amplitudes of zonal harmonic field coefficients  $Z^0$ ,  $Z^1$ ,  $Z^2$ , ..., normalized to a defined diameter spherical volume.

Even such "long bore" magnets had some magnetic field inhomogeneities. Some of the inhomogeneities were attributable to build or manufacturing errors, and some were due to limiting or theoretical characteristics of the magnet design. Such long bore magnets typically had harmonic distortions, due to build errors, on the order of  $Z^0$  through  $Z^6$ . To correct these inhomogeneities, ferrous shims were mounted along the patient receiving bore. These lower order harmonics were cured with a minimal amount of ferrous material. In some imagers, the shims were mounted inside the bore and in others they were mounted outside the bore, e.g., in a superconducting magnetic's cryo-vessel. Typically, shim trays were constructed of a non-ferrous material. The pockets of the non-ferrous trays received ferrous shims, e.g., thin plates of steel coated with a non-conductive polymer or oxide coating. The shims were constrained in the pockets and the trays were mounted inside or outside of the bore.

In magnetic resonance imagers, a magnetic field gradient coil was mounted inside the magnet's bore. Typically, the gradient coil assembly was mounted radially inward from the shims. Imagers with self-shielded gradient coils had a main or primary magnetic field gradient coil and a shield or secondary magnetic field gradient coil which were mounted in a spaced relationship. The shield gradient coil was often placed outside of the bore and, in a superconducting magnet imager, could be placed within the cryo-vessel. With self-shielded gradient coils, the shim trays were often positioned between the primary and shield gradient coils. See, for example, U.S. Patent No. 5,349,297.

A radio frequency coil was mounted radially inward from the gradient coil(s). A radio frequency shield was mounted between the radio frequency coil and the gra-

dient coils. The radio frequency shield blocked radio frequency signals from reaching the gradient coils, the shims, and other surrounding constructions in which eddy currents could be induced. Radio frequency eddy currents would generate radio frequency signals which would be transmitted into the interior of the radio frequency coil. The eddy radio frequency signals lowered the signal-to-noise ratio during reception of resonance signals and increased the power demands on the radio frequency coil during radio frequency transmission. In addition, the radio frequency shield blocked the transmission of any noise conducted into the bore via the gradient coils.

A cosmetic liner was commonly positioned radially inside the radio frequency coil to prevent the imaged patient from touching the radio frequency and gradient coil constructions and for cosmetic purposes.

One of the difficulties with such magnetic resonance imagers is that the 1.5 to 2.0 meter long bores were claustrophobic to many patients. The long bores also prevented medical personnel from accessing the patient while in the bore. Typically, to perform a medical procedure based on the diagnostic images, the patient needed to be removed from the bore and the diagnostic images reregistered with the patient in the new patient position. If a probe, such as a biopsy needle, was inserted into the patient and the physician wanted to check with the magnetic resonance imager whether it was inserted to the proper location, the patient and probe needed to be reinserted into the bore for another imaging session.

One solution to these problems resides in the use of "short bore" magnets, e.g., 1.25 meters or less. Although short bore magnets render the imager more user friendly and provide improved access to the patient, the temporally constant magnetic field generated by the short bore magnets tends to be less homogeneous. Moreover, such short bore magnets typically have higher than  $Z^6$  order harmonic distortions, intrinsic to the magnet design, to be shimmed. Higher order distortions require significantly more ferrous material for shimming than do  $Z^6$  and lower order distortions.

In accordance with one aspect of the present invention, a magnetic resonance apparatus is provided. Magnets are disposed in a toroidal housing for defining a temporally constant magnetic field through a central bore of the toroidal housing. A radio frequency coil is disposed in the bore. A radio frequency shield is disposed around the radio frequency coil. Segmented ferrous material is disposed in annular rings around the bore. The segmented ferrous material rings are disposed between the radio frequency coil and the radio frequency shield.

Preferably the radio frequency shield is disposed between the segmented ferrous material rings and the gradient coil assembly.

Preferably the segmented ferrous material includes one of ferrous plates with an insulating coating, ferrous

rods, ferrous strips, ferrous wire, and powdered ferrous material.

In accordance with another aspect of the present invention, a method of shimming a magnetic resonance imaging apparatus is provided. The imaging apparatus includes magnets disposed in a toroidal housing for defining a temporally constant magnetic field through its central bore. A gradient magnetic field coil assembly is disposed along the bore of the toroidal housing for causing gradients in the temporally constant magnetic field within the bore. A radio frequency coil is disposed radially inward from the gradient magnetic field coil assembly. A radio frequency shield is disposed between the gradient magnetic field coil assembly and the radio frequency coil. The method includes positioning rings of segmented ferrous material around the bore immediately contiguous to the radio frequency coil to adjust magnetic field uniformity of the temporally constant magnetic field.

One advantage of the present invention is that the volume and massing of steel needed to shim higher order distortions is reduced, in the preferred embodiment by about a factor of 4.

Another advantage of the present invention is that radio frequency and gradient eddy currents in the shims is reduced.

Another advantage of the present invention resides in its compact design. The dimension between the magnets for generating the temporally constant magnetic field and the inside of the radio frequency coil is reduced. This allows a ratio of the patient bore diameter to the magnet diameter to be increased.

Another advantage of the present invention is that the shim material is isolated from the gradient magnetic field coil. Isolating the shims from the gradient magnetic field coil reduces vibrational effects due to interaction between the two. It also eliminates changes in the shim steel's magnetization due to temperature fluctuations associated with heating by the gradient coil. Gradient coils are often required to dissipate a few to 15 kilowatts or more due to resistive losses, causing temperature changes on the order of 40° C.

The invention will now be further described by way of example with reference to the accompanying drawings in which:-

FIGURE 1 is a diagrammatic illustration, in partial section, of a magnetic resonance imager in accordance with the present invention;

FIGURE 2 is a detailed illustration of the radio frequency coil, the gradient coil assembly, and the shimming assembly of FIGURE 1;

FIGURE 3 is an exploded view of the radio frequency coil and shimset assembly of FIGURE 1;

FIGURE 4 illustrates an alternate embodiment to the shim ring of FIGURE 2;

FIGURE 5 illustrates another alternate embodiment of the shim rings;

FIGURE 6 illustrates another alternate embodiment of the shimming material;

FIGURE 7 is a sectional view of an alternate embodiment of the shimming material;

FIGURE 8 is another embodiment of the shimming system of the present invention; and,

FIGURE 9 is a cross-sectional view illustrating yet another embodiment of the shimming material.

With reference to FIGURE 1, a plurality of superconducting magnetic field coils, including primary coils 10 and shield coils 12, generate a temporally constant magnetic field. Within an imaging region at the geometric center of a bore 14, this magnetic field is substantially uniform and extends axially along a longitudinal or z-axis. X and y-axes are typically assigned to horizontal and vertical directions. In the preferred embodiment, the patient receiving bore of the magnetic resonance imaging apparatus has a length-to-diameter ratio of 1.6:1 to 1:1 or less. The superconducting magnetic field coils are disposed within a toroidal helium vessel or can 16. The helium vessel is filled with liquid helium to maintain the superconducting magnet coils at superconducting temperatures with the impressed magnetic field.

To reduce helium boil-off, the toroidal helium vessel 16 is surrounded by a toroidal vacuum vessel 18. One or more cold shields 20 are disposed between the vacuum vessel 18 and the helium vessel 16. The cold shields and the interior of the vacuum vessel are preferably chilled by mechanical refrigeration. Layers of aluminized mylar insulation are arranged between the vacuum vessel, the cold shields, and the helium vessel.

With continuing reference to FIGURE 1 and further reference to FIGURE 2, the vacuum vessel 18 includes a cylindrical wall 30 surrounding the bore. A primary gradient coil assembly 32 is mounted on an inner diameter of the dielectric cylinder 30. In the illustrated embodiment, the primary gradient coil includes a dielectric former 34 having grooves which receive annular z-gradient coil windings 36. X and y-gradient coils 38, 40 are wrapped around the dielectric former 34. Preferably, the gradient coils are potted in epoxy or the like.

A secondary or shield gradient coil 42 includes z-gradient shield coils 44 mounted in grooves in the dielectric cylinder 30. X and y-shield coils 46, 48 are wrapped around the dielectric cylinder 30.

The primary and secondary gradient coils are held in a spaced relationship by a plurality of radial spacers 50 such that a plurality of longitudinally extending pockets are defined between the primary and shield gradient coils. Shim trays 52 are mounted in the passages between the primary and secondary gradient coils. The shim trays 52 are constructed of a dielectric material that defines a series of pockets within which ferrous shims 54 are mounted. The distribution of shims along the shim tray is selected to optimize the uniformity of the magnetic field from the magnets 10, 12 in the imaging region. This region may be defined as an ellipsoidal, a circular cylindrical, or a spherical volume. The shims 54

are preferably thin plates of silicon steel that are coated with a dielectric material. Both grain-oriented and non-oriented steels may be used.

A radio frequency shield and shim assembly **60** includes a dielectric cylinder **62**. The dielectric cylinder **62** has annular grooves **64** formed therein. For a given magnet design, the higher order distortions are predictable. Alternately, an initial magnet of a given design can have its magnetic field measured in the imaging region and corrections for the higher order harmonics calculated. The location of the grooves is selected in the dielectric ring **62** in accordance with the groove location measured for prior magnet systems. As yet another alternative, the field of each magnet assembly is measured and the grooves are custom cut. Ferrous shims **66** are mounted in the annular grooves **64**.

A resilient mounting **68** connects the dielectric cylinder **62** with the primary gradient coil **32** in a non-vibration transmitting relationship. In this manner, any movement or vibration of the shims **66** due to interaction with the magnetic field gradients is minimized to maintain temporal stability of the main field.

A radio frequency coil assembly **70** is mounted inside the inner surface of the shimming coil assembly **62**. In the illustrated embodiment, the radio frequency coil assembly includes conductive end rings **72** at opposite ends of the inner surface of the dielectric cylinder **62**. Optionally, a cosmetic face plate **74** (not shown in FIGURE 2) covers the conductive rings **72** and the inner surface of the dielectric cylinder **62**. A series of connectable and disconnectable radio frequency coil elements or legs **76** are releasably connected with the annular rings **72**. The coil elements are encased in a dielectric material. By connecting different legs **76** with the annular end rings **72**, birdcage coils with different numbers of legs or differently tuned legs and characteristics can be assembled. Of course, radio frequency coils with fixed legs, as shown in FIGURE 2, are also contemplated.

A radio frequency shield **78** is disposed around the outer surface of the cylinder **62**. The RF screen, in one embodiment, is a copper mesh. Other RF screens such as slotted copper foil and the like are also contemplated. In the illustrated embodiment, the RF screen passes over the shim rings **66** such that the shim rings are inside the radio frequency shield. Alternately, the radio frequency shield can be configured to conform with the annular grooves **64** and be mounted to the cylinder **62** prior to loading of the shims **66**. Optionally, the radio frequency coil can be a separate structure which is slidably inserted into the bore of the dielectric cylinder **62**. For example, the radio frequency coil may be constructed of copper foil strips adhered to the surface of a light-weight dielectric cylinder.

With reference to FIGURE 3, in one preferred embodiment, dielectric members **80** fit within the groove **64**. Each dielectric member **80** has a series of pockets **82** which receive an appropriate stack of the shims **66**.

In the embodiment of FIGURE 4, a series of metal shims **66**, each covered with a thin dielectric coating,

are adhered to a flexible strip **84**. Preferably, the shims **66** are mounted in a lapped or scale-like fashion to the flexible strip **84**. The strip **84** and the shims are dimensioned to be received within the groove **64**. The strip of shims are wrapped around the groove **64** one or more times as may be appropriate to provide the prescribed mass of ferrous material.

With reference to FIGURE 5, the ferrous material may be in other forms than thin plates. For example, ferrous wires or strips **86** can be mounted in a closely spaced relationship on an insulating flexible dielectric layer **84** or between two such layers.

With reference to FIGURE 6, the ferrous material can also be in powdered form. In the illustrated embodiment, the flexible dielectric material **84** defines a series of pockets which are filled with powdered ferrous material **88**. The strip **84** is again wrapped around the groove **64** until the required ferrous mass is achieved. Alternately, the powdered ferrous material can be mixed with an epoxy or other bonding agent and be applied to the grooves like a cement or putty or as pre-cured shims of various thicknesses.

With reference to FIGURE 7, the powdered ferrous material **88** is encased in a flexible dielectric matrix **90**. Strips of the flexible dielectric matrix with encased ferrous powder are wrapped in the grooves **64**. The ferrous powder elements may be microspheres, microrods, or other structure with a high packing factor.

With reference to FIGURE 8, the segmented ferrous rings are defined by circumferentially aligned pockets **92** of trays **94** that are inserted longitudinally into the dielectric cylinder **62**. Ferrous shims, such as ferrous plates, powders, and the like, are loaded into the pockets **92** to define the circumferential rings.

With reference to FIGURE 9, the ferrous shim material, a submillimeter ferrous wire **96** is wound on the dielectric cylinder or in the groove **64** in a tightly packed bundle. An epoxy matrix **98** insulates the turns of the fine wire from each other. Optionally, the wire may be composed of braided fiber segments.

Various other techniques for loading the grooves **64** with a preselected amount of ferrous material are also contemplated. The ferrous material is in relatively small sections to limit eddy currents induced by the radio frequency coil in the transmit mode and to limit eddy currents induced by the gradient coil assembly. Eddy currents limited to small spatial regions die out relatively quickly and are relatively weak. Thin rods and powdered material have a very limited ability to support eddy currents. On the other hand, if continuous metal flat loops were positioned around the examination region, sufficient eddy current and z-gradient mutual coupling problems could be expected. The present invention enables annular iron shims to be constructed from discontinuous steel elements. In this manner, effective shimming is provided while inhibiting detrimental eddy currents.

In use, the magnetic field inhomogeneity is calculated or measured using a magnetic field probe. For example, an initial magnetic resonance imaging appara-

tus can have its magnetic fields measured on the surface of a spherical imaging volume using a magnetic field measuring probe and appropriate masses and positions of shimming material calculated. In subsequently manufactured scanners, the placement and mass of steel for shimming higher order components will be similar. Accordingly, the annular shimming assembly 60 can be initially manufactured to be substantially the same from machine to machine. After preliminary assembly, the magnetic field is measured and the ferrous mass and position requirements for further shimming are determined. Based on these determinations, the shims 54 and the shim trays 52 can be adjusted, as can the shimming in the annular shim assembly 60. For significant shimming for higher order components, adjusting the mass of ferrous material in the annular shim assembly 60 is preferred. For fine adjustments in high or low order distortions, adjusting the shims in shim tray 50 can be done conveniently.

With reference again to FIGURE 1, a sequence control 100 controls a gradient control 102 and a radio frequency transmitter 104. The gradient control 102 is connected with a series of current pulse generators 106, which, in turn, are connected with the primary gradient coils 32 and the secondary gradient coils 42. The radio frequency transmitter 104, preferably a digital transmitter, is connected with the radio frequency coil 70 for generating pulses of radio frequency signals for exciting and manipulating magnetic resonance in selected dipoles of a portion of a subject within the imaging region of the bore. A radio frequency receiver 108, preferably a digital receiver, is connected with the radio frequency coil 70 or surface coils (not shown) for demodulating magnetic resonance signals emanating from the portion of the subject in the examination region. An image reconstruction processor 110 reconstructs the received magnetic resonance signals into an electronic slice or volume image representation, preferably by using a two-dimensional Fourier type transform reconstruction algorithm. The electronic image representation is stored in an image memory 112. A video processor 114 converts selectable slices or other portions of the electronic images stored in the image memory 112 into appropriate format for display on a human-readable monitor 116.

## Claims

1. A magnetic resonance apparatus including a plurality of magnets (10, 12) disposed in a toroidal housing (18) for defining a temporally constant magnetic field through a central bore (14) of the toroidal housing, a radio frequency coil (70) disposed in the bore, and a radio frequency shield (78) disposed around the radio frequency coil (70), characterized by:

segmented ferrous material (66) disposed in annular rings around the bore (14), the segmented ferrous material rings being disposed between the

radio frequency coil (70) and the radio frequency shield (78).

2. A magnetic resonance apparatus as claimed in claim 1, including:

a gradient magnetic field coil (32) between the toroidal housing and the radio frequency shield;

a plurality of shim trays (52) disposed radially outward from the gradient magnetic field coil, the shim trays (52) carrying selectively adjustable numbers of ferrous shims (54).

3. A magnetic resonance apparatus as claimed in claim 1 or 2, including a cylindrical dielectric tube (62) having a plurality of annular grooves (64) defined in an outer circumference thereof, the segmented ferrous material rings (66) being mounted in the grooves (64).

4. A magnetic resonance apparatus as claimed in any one of the preceding claims wherein, the segmented ferrous material (66) includes one of:

ferrous plates with an insulating coating, ferrous rods, ferrous strips, ferrous wire, and powdered ferrous material.

5. A magnetic resonance apparatus as claimed in any one of the preceding claims, wherein the radio frequency shield (78) is disposed between the segmented ferrous material rings (66) and the gradient coil assembly (32) such that the ferrous material (66) is on the same side of the radio frequency shield (78) as the radio frequency coil (70).

6. A method of shimming a magnetic resonance imaging apparatus which includes a plurality of magnets (10, 12) disposed in a toroidal housing (18) for defining a temporally constant magnetic field through a central bore (14) of the toroidal housing, a gradient magnetic field coil assembly (32) disposed along the bore of the toroidal housing (18) for causing gradients in the magnetic field within the bore, a radio frequency coil (70) disposed radially inward from the gradient magnetic field coil assembly (32), and a radio frequency shield (78) disposed between the radio frequency coil (70) and the gradient magnetic field coil assembly (32), the method characterized by:

positioning rings of segmented ferrous material (66) around the central bore (14) immediately contiguous to the radio frequency coil (70) to adjust magnetic field uniformity of the temporally constant magnetic field.

7. A method as claimed in claim 6 further including the step of positioning the ferrous material (66) includ-

ing positioning the ferrous material in annular grooves (64) of a dielectric tube (62).

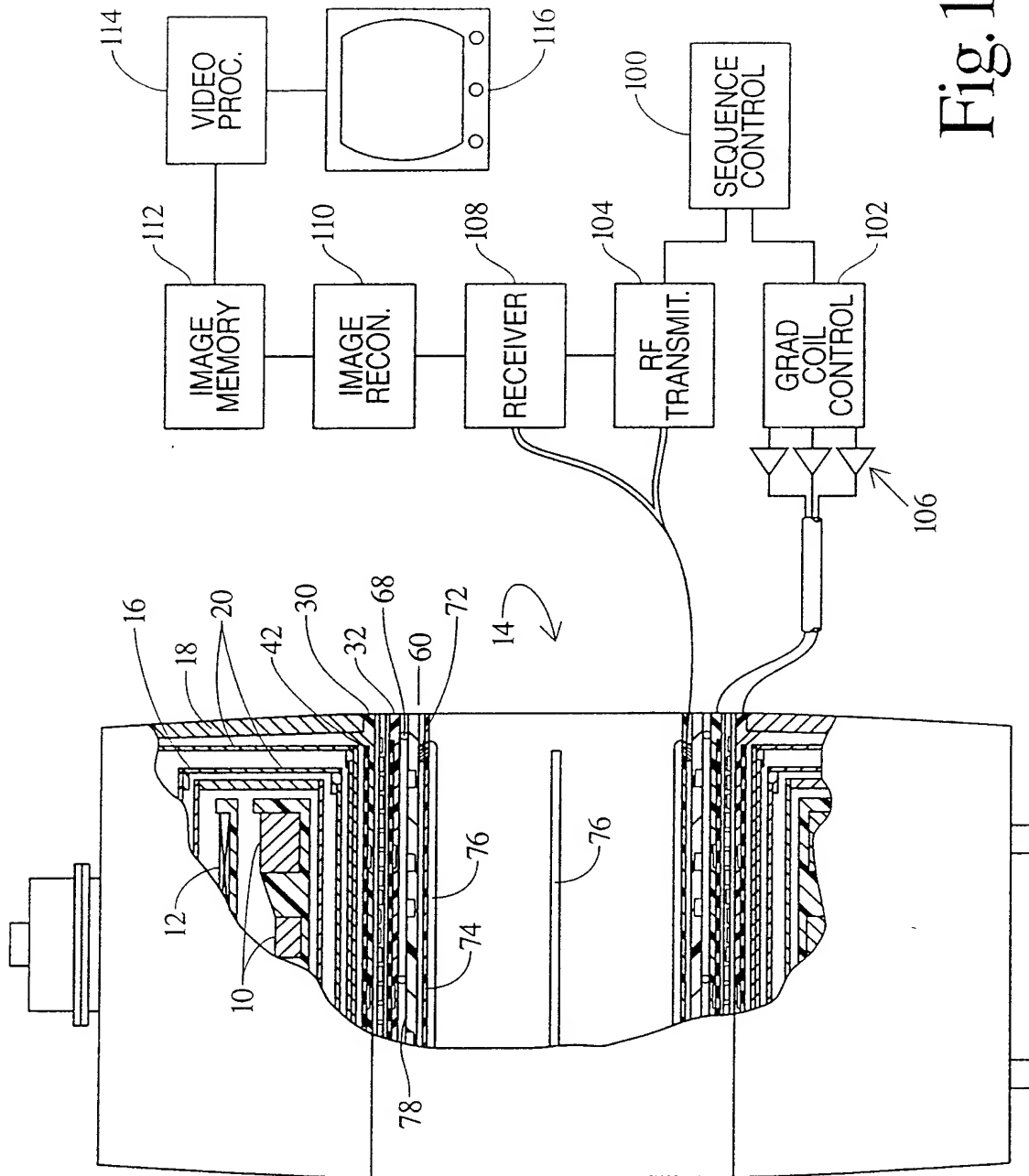
8. A method as claimed in either of preceding claims 6 and 7, wherein the ferrous material (66) is disposed in association with a flexible carrier (84) and the step of applying the ferrous material (66) includes wrapping the flexible carrier (84) around the dielectric tube (62).

9. A method as claimed in any one of claims 6, 7, and 8, wherein the ferrous material (66) includes one of:

ferrous plates with an insulating coating, ferrous rods, ferrous strips, ferrous wire, and powdered ferrous material.

10. A method as claimed in any one of claims 7 to 9, further including:

disposing longitudinal trays (52) parallel to the bore (14) radially outward from at least one gradient coil of the gradient magnetic field coil assembly (32), the trays (52) carrying selectively adjustable masses of ferrous material (66);  
measuring a uniformity of the temporally constant magnetic field within the bore (14);  
adjusting the mass of ferrous material (66) carried by the trays (52) in accordance with the measurement; and,  
adjusting the mass of ferrous material (66) in the annular rings in accordance with the measurement.



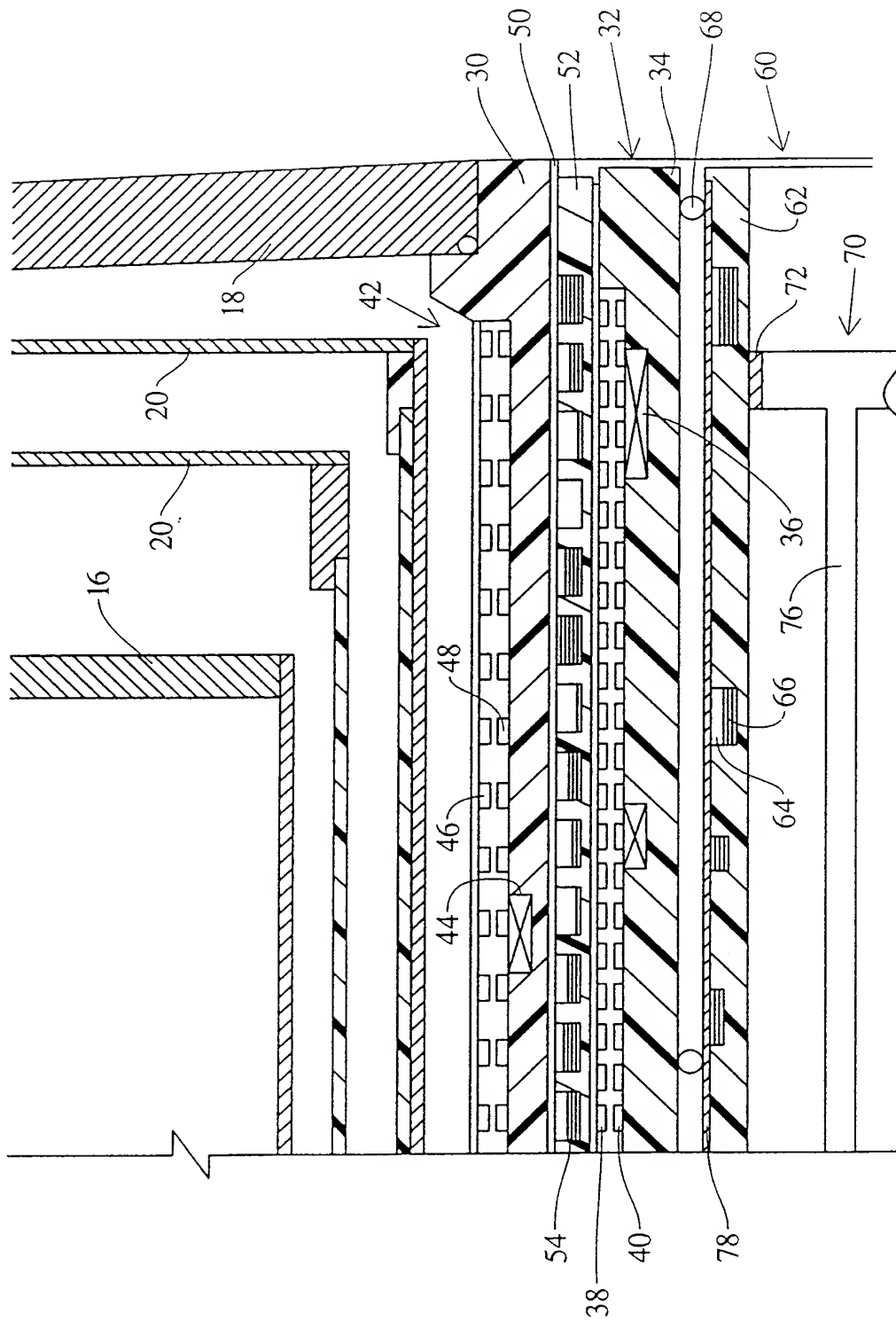
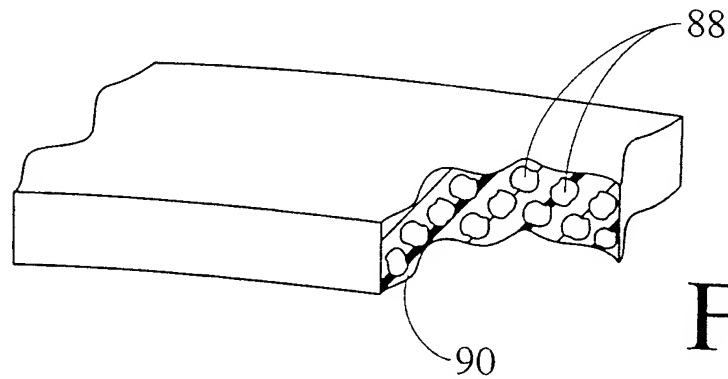
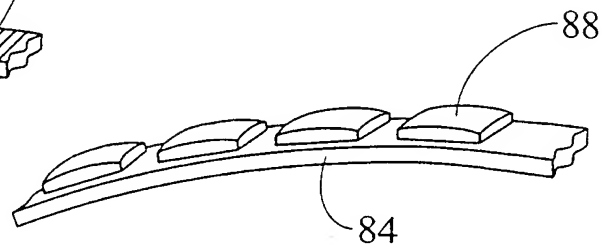
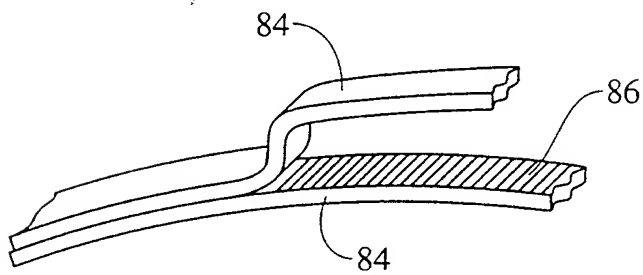
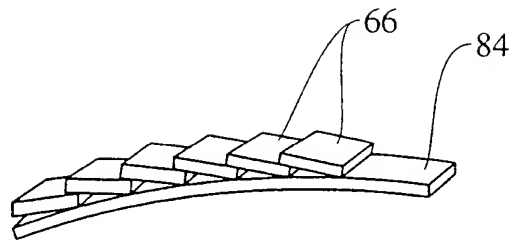
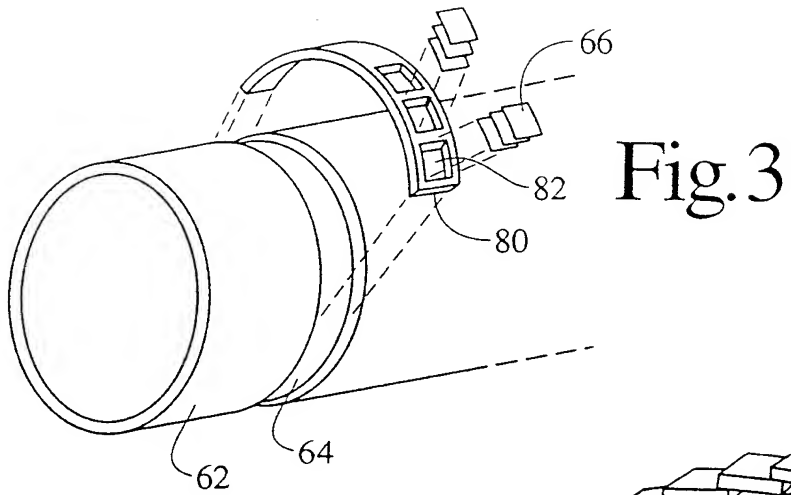


Fig.2





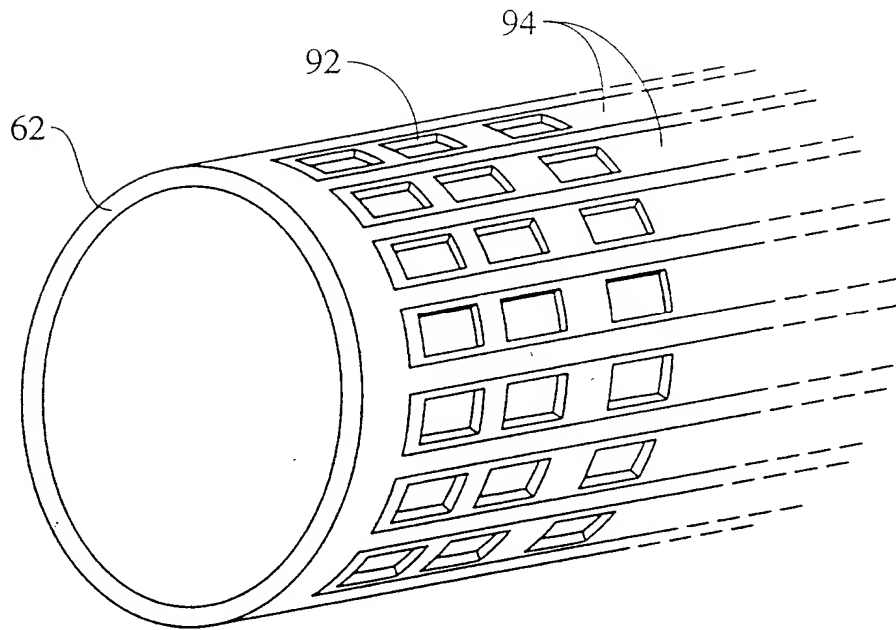


Fig. 8

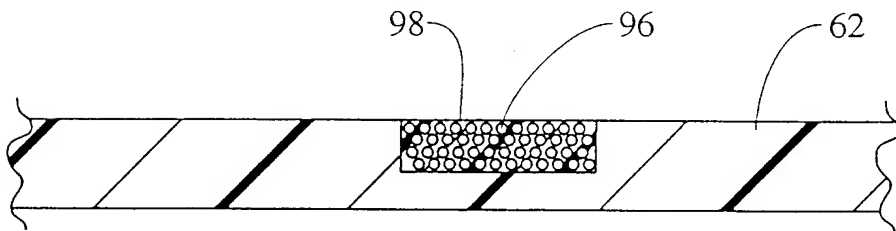


Fig. 9



European Patent  
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# EUROPEAN SEARCH REPORT

Application Number  
EP 96 30 1853

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	EP-A-0 629 873 (PICKER INTERNATIONAL, INC.) * column 2, line 17 - column 3, line 38 * * column 4, line 37 - column 5, line 20 * * column 5, line 43 - column 6, line 21 * * figure 2 *	1-4,6-10	G01R33/3873
D	& US-A-5 349 297 ---		
A	EP-A-0 216 404 (N.V. PHILIPS' GLOEILAMPENFABRIEKEN) * page 2, line 4 - page 3, line 16 * * page 5, line 27 - page 8, line 24 * * figure 1 *	1,6	
A	DE-A-40 21 345 (MITSUBISHI DENKI K.K.) * page 2, line 22 - page 3, line 17; figures 1,2 * -----	1,6	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			G01R
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 14 August 1996	Examiner Volmer, W
<p><b>CATEGORY OF CITED DOCUMENTS</b></p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ..... &amp; : member of the same patent family, corresponding document</p>			

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